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DIGITAL IMAGE ANALYSIS SYSTEM FOR MONITORING CRACK GROWTH AT ELEVATED TEMPERATURE

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1. SUMMARY

The objective of the research work reported here was to develop a new concept, based on Digital Image Analysis, for monitoring the crack-tip position at elevated temperatures.

The proposed system includes:

a) CCD camera observing the crack-tip.

b) PC-based frame grabber, capturing a 512 x 512 pixel frame.

c) Digital Image Analysis software developed to locate and digitize the position of the crack-tip, on the observed image area.

d) Step-motor driven stage, permitting the image-transmitting penetrator to follow-up the tip as it advances.

e) A penetrator (fiber-optic or lenses) transmitting the magnified image from the vicinity of the crack-tip to the camera.

In the course of the research work, the system was designed, assembled, and tested. Also, a program was developed for digitizing the crack-tip position. To evaluate the feasibility of the concept, its potential accuracy, resolution, temperature limitation and usefulness the system was tested at room and elevated temperature.

The results of the testing and evaluation prove that the proposed concept is feasible, practical, and capable of performing at temperatures exceeding our initial objectives.

Potential Application of the Research Results

The measurements of crack-tip advance is performed daily by hundreds of laboratories, investigating material fatigue properties and fracture behavior. These measurements are labor-intensive operations, requiring fequent microscope-assisted observation and delicate micrometer-eyepiece adjustments. The precision required is difficult to achieve, using visual judgment. Still the results of these measurements are critical in the design and in assessing the performance of critical components subjected to cyclic loads and vibration, such as turbine blades, aircraft structural components and hundreds of other structural elements in automotive industry.

The newly developed concept, using Digital Image Analysis as replacement of the visual follow-up, and offers:

- Labor saving
- Automation of the data acquistion.
- Objective interpretation
- Extension to 2000° F and above, not presently feasible

We expect that the system, when fully developed, will find a broad commercial market.

2. PHASE I RESEARCH OBJECTIVES

The objective of the Phase I research reported here was to develop and evaluate the feasibility of a novel system, capable of monitoring the crack-tip progress at elevated temperature reading 2000° F, using Digital Image Analysis for observation and location of the crack-tip coordinates.

The successful completion of this research demonstrated the feasibility of a potentially powerful tool for in-situ, real-time, automated crack-tip propagation monitoring. The developed methodology, not only significantly increases the accuracy of the crack-tip determination, but it also eliminates the uncertainty associated with the human decision on the exact location of the crack-tip. In addition, a correct log of crack-tip position versus actual time and number of cycles is automatically saved in a computer readable form, thus allowing for immediate analysis with any applicable software packages.

The importance of this newly developed technique, reported here, is further emphasized by an extensive round-robin study conducted by fifteen different laboratories with several test specimen geometries, in order to develop a recommended practice for fatigue crack-growth rate testing. The results of this study (1) were evaluated statistically, and the variability and bias associated with both analytical and experimental aspects of crack-growth rate testing were determinated.

The results of the study showed that the primary source of variability associated with fatigue crack-growth rate testing is the experimental procedure used to obtain the raw test data - crack length versus elapsed cycles.

The problems and difficulties associated with accurate crack-tip position monitoring are multiplied ten-fold. when there is a need for a high-temperature application.

A recently published paper (2) described the work on crack-growth evaluation in INCONEL 718 Alloy at 650° C. This work was based mainly on the experimental data derived from the crack-tip position measured at this high temperature. Another application was presented (3), where crack-growth rate was evaluated in the blade of a modern gas turbine, which operates at 925° C. During each flight, this component undergoes a large number of thermally induced stress-strain cycles, which may cause crack growth. Those and many other examples point to the necessity of an accurate, non-contact technique for automated data acquisition for the crack-tip position.

The research undertaken in this project faced the technical challenge of integrating the known principles of the visual crack-tip monitoring approach with the Digital Image Analysis system to create a working system capable of automated monitoring of the fatigue crack-growth rate. Since the modern Digital Image Analysis system components became easily available, several uses for experimental strain and stress analysis were developed. Applications to photoelasticity and Moire were recently described elsewhere (4, 5).

Newly developed materials for high-temperature application need to be tested, and data has to be acquired for crack-growth rate versus number of loading cycles. This process is extremely complicated and, because of the need for constant human interaction with the data gathering, is prone to human errors. Those errors may destroy efforts of the long and expensive high-temperature test. The methodology developed and described here can be extended to high-temperature applications, opening a new avenue for the testing without all the difficulties associated with human interpretation of the crack-tip position. Only the high-temperature quartz lenses will be exposed to the realm of 2000-2500° F heat.

All the necessary optical information is transmitted to a CCD video camera through an organized fiber-optic bundle, thus eliminating any human interference with the process of data gathering. Human intelligence is needed for data analysis, interpretation and conclusions, not for data acquisition, which can be handled much more efficiently and accurately by computer-based Image Analysis system.

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3. DESCRIPTION OF THE PROPOSED MEASURING SYSTEM FOR MONITORING CRACK GROWTH

The system using the DIA for monitoring the crack-tip position is shown schematically on the Figure 1.

The specimen under investigation is subjected to a cycling load at room or elevated temperature. As a result of loading spectrum, the crack length "a" increases. The crack growth Δa must be recorded as a function of time or number of load cycles N, in order to evaluate the material toughness, of other desired material properties. The region that includes the crack-tip is observed by the CCD-TV camera, and the acquired image is digitized and stored in a 512 x 512 points (pixel) format by the IMAGE GRABBER board, installed in a PC-AT computer. This stored quantitative photo is then analyzed, looking for discontinuities in a vertically scanned light intensity, revealing the a(x) and a(y) position of the crack-tip. As the crack-tip advances, a new "x" (or "y") position of the tip reveals quantitatively the crack length increase Δa, as function of time, or function of number of cycles N.

As the crack approaches the end of the area observed by the camera, a stepping motor is instructed to drive the stage, moving the camera to a new position, defined by the program and selected in accordance with the observed field of view.

The scan for measuring Δa can be continuous, or can be initiated by time interval (a vs. time) or N count (a vs. N). In the system that was used, the scan time for one frame acquisition was 1/30 seconds.

One monitor is used to display a(x) and the prompts for the system operation, while the other monitor displays the image observed and is useful for initial focusing and position adjustments.

Since in most installations the furnace windows are too small to properly follow-up a long crack, and are too far from the specimen to provide adequate magnification, a penetrator was developed for carrying the image from the vicinity of the crack-tip back to the camera. The penetrator moves together with the camera and follows the crack-tip, permitting the observation of the crack-tip at high magnification. The span of the follow-up was 100mm (4 in.).

Strainoptic and Dr. Voloshin of Lehigh University developed software for interpretation of the observed image and retrieval of information. The software permits the measurements of the crack-tip position advance, issues command to the stepping motor and interprets the a vs. N information in terms of the fracture mechanic parameters.

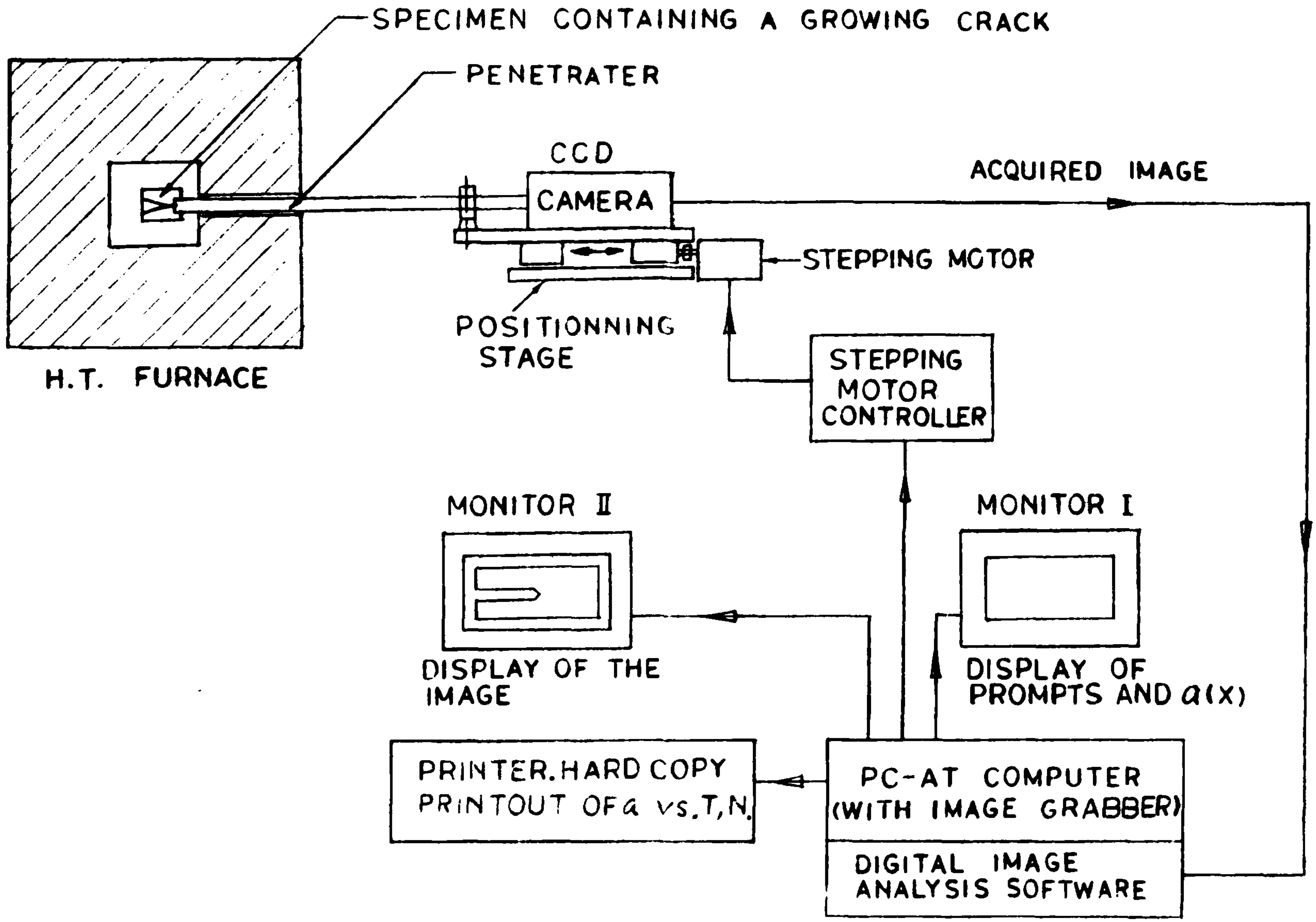

FIGURE: 1 SYSTEM SCHEMATIC

3.1. Transmission of the Specimen Image to the Digital Analysis System

A. Visual Observation of the Crack-Tip Position

Using visual inspection, the region of the specimen containing the tip of the crack is directly observed using a microscope at low to medium magnification level. Use of high magnification is not practical, since it limits the size of the observed area and makes it difficult to see reference marks or scale.

a) The crack-tip progress can be monitored using a micrometer eye-piece in the microscope, measuring the distance to the nearest reference line, on the specimen, or on the attached scale.

b) As an alternative solution, a traveling microscope (or telescope) can be used. The cross-hair of the eyepiece is moved to the new crack-tip position, and the measured motion provides then the crack-tip advance.

The above visual procedures require skill and experience, mostly when using a micrometer eyepiece. The procedure (b) does not account for the lateral motion of the specimen, and is mostly use-ful for room temperature observation.

The visual observation at elevated temperature becomes difficult. Using a window, one can see the specimen and use the procedures (a) or (b) above, provided the window size is sufficiently large to follow-up the crack-tip. The hot air motion introduces a random fluctuation of the image affecting seriously the visibility and the precision.

The visual observation is labor-intensive, lacks the continuity and becomes impractical at high temperature.

3.1.1. Image Transmission for Digital Image Analysis

The concept of measuring the crack-tip position using the Digital Image Analysis is similar to the visual concept, except that the analysis of the image is performed by the computer, rather than human interpretation.

The logic of the image interpretation needed to locate the tip of the crack is discussed in 3.4.1 below.

Once the crack-tip position is digitized, the progress can be measured using approaches similar to visual (a) and (b) above, measuring the crack-tip positon with reference to:

- Previous position
- Reference on the specimen
- Edge
- Translator stage position

Three methods of the image transmission to the camera are possible, and were analyzed for their practical usefulness in this study.

3.1.1.1 Direct Observation

Figure 2 below shows schematically the direct observation concept.

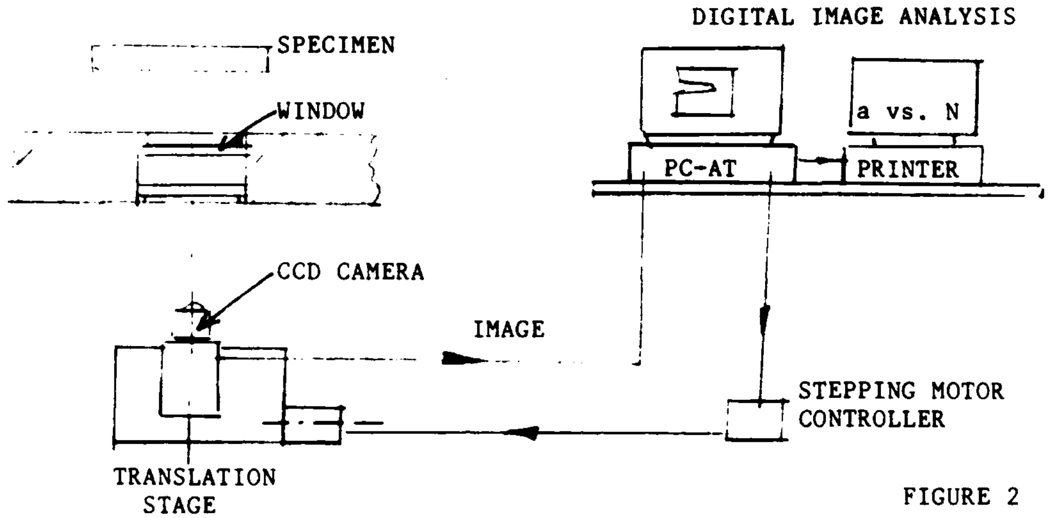

FIGURE 2

For room temperature testing, this is a simple and practical solution. The CCD camera observes directly the specimen. The camera is mounted on a digitally-controlled translation stage that moves the camera to a new position, whenever the crack progress requires repositionning.

At elevated temperature, this approach is less practical, since it requires a large access window. Also, as mentioned above, hot air currents degrade the image quality and the resolution.

3.1.1.2 Penetrator

In order to eliminate the difficulties due to a limited window size, and hot-air eddies typical of direct observation, a penetrator was designed to carry the image from the specimen to the camera.

The penetrator requires only a small 20 mm ($\frac{3}{4}$ in.) diameter hole in the furnace side-wall and permits to locate the objective lens (1) within approximately 15 mm (5/8 in.) from the specimen, reducing considerably the image distortion due to the hot-air motion.

Two designs (Figures 3 and 4) were tested for evaluation of their relative merits and limitations.

a) <u>Fiber-Optic Penetrator</u>

In the fiber-optic penetrator design, the objective lens (1), (See Figure 3) forms the image of the tip of the crack on the face of a fiber-optic image-transmitting guide.

The same image (1:1 ratio) is transmitted and becomes visible at the other end of the guide, and projected by means of the camera imaging lens (2) (Figure 3) on the CCD sensor of the camera.

b) <u>Relay-Lens Penetrator</u>

The relay-lens penetrator is identical to the above design, except that it replaces the fiber-optic guide by a set of relay lenses (See Figure 4) to carry the image of the crack-tip to the camera sensor.

In both (a) and (b) penetrator designs (Figures 3 and 4), the length of the penetrator was arbitrarily set at 300 mm (12"), and the OD at 19 mm ($\frac{3}{4}$ in.) fitting our high-temperature furnace. The specimen side (lens 1) was equipped with a fused-silica lens, and right-angle prism, forming the image on the tip of the image guide.

On the camera-side a glass lens was used to project the fiber-optic image guide on the camera CCD chip. For the fiber-optic pentrator, the IMAGE GUIDE was selected after reviewing several suppliers. The IMAGE GUIDE procured for experimentation was 6.35 mm diameter coherent bundle, consisting of fused 12 micron preform fibers.

For the relay-lens penetrator, a telecentric lens system was designed, including quartz lenses at the hot end, and glass lens at the camera end.

The relative performance of these concepts is discussed in Test Results and Conclusions.

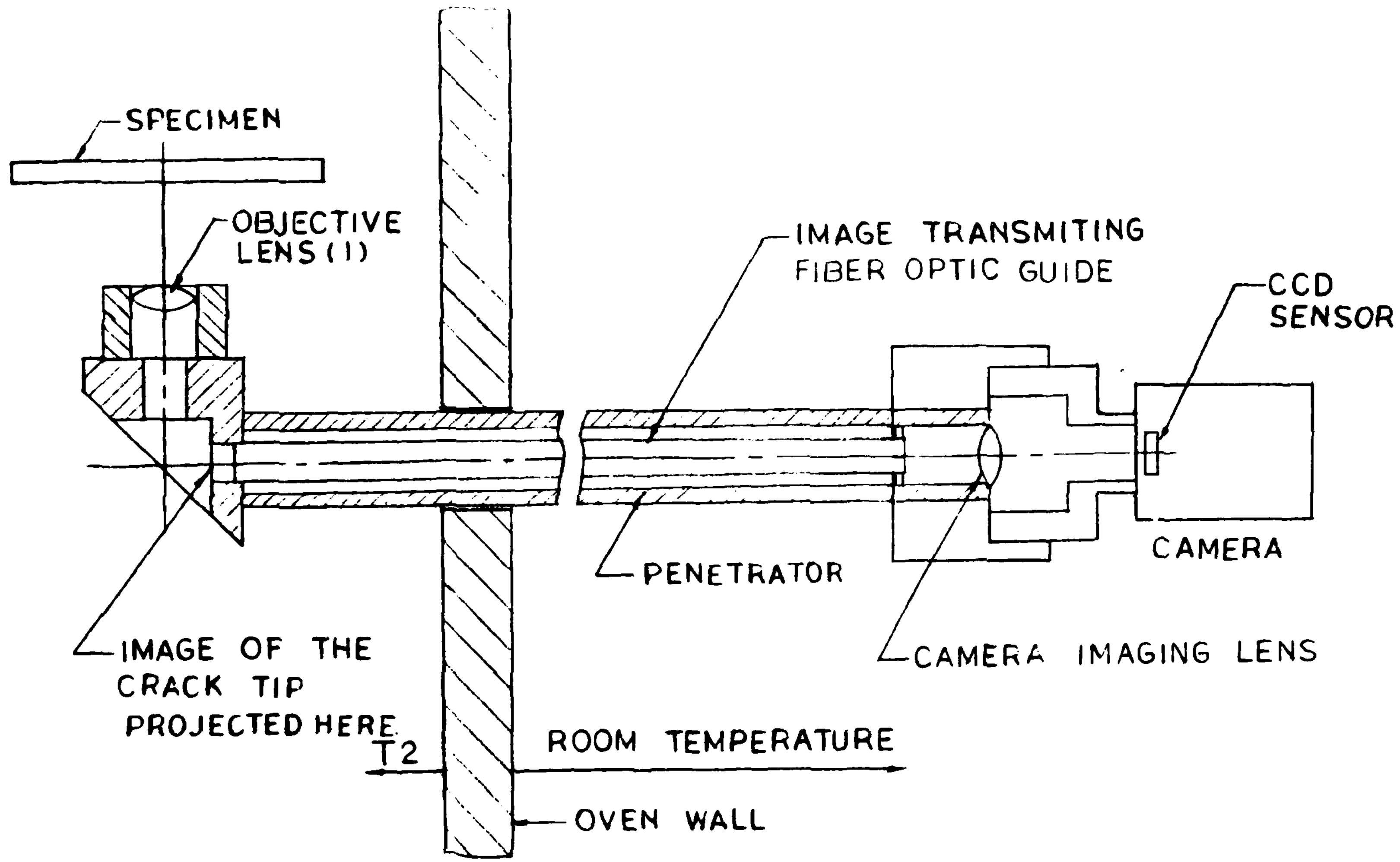

FIGURE: 3 IMAGE TRANSMISSION USING FIBER-OPTIC GUIDES

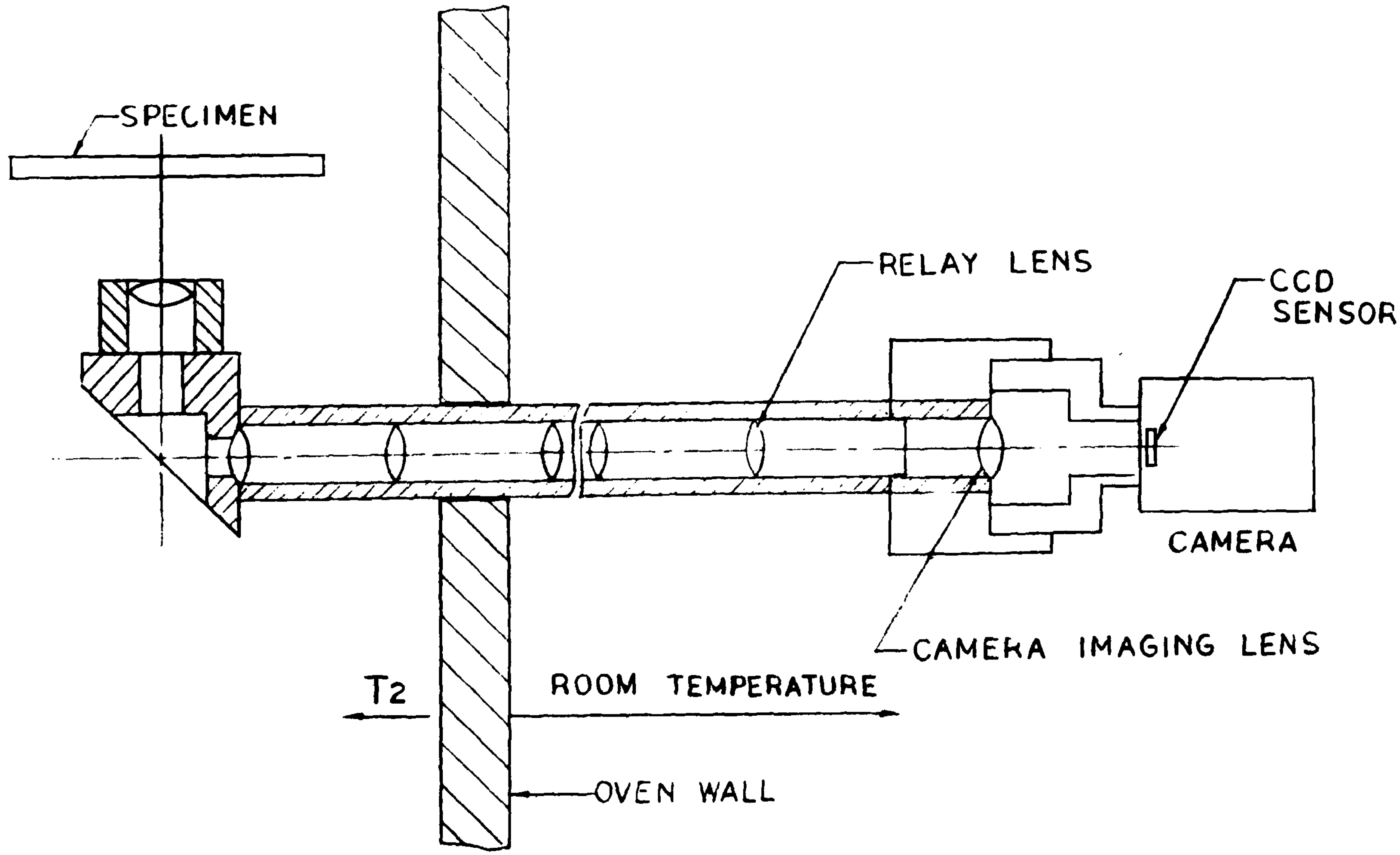

FIGURE: 4 IMAGE TRANSMISSION USING RELAY LENSES

3.2. Linear Motion, Digitally Controlled Stage for Positionning of the Viewing Camera and Penetrator (Figure 5)

The objective of this stage is to automatically position the viewing head, that includes the CCD camera with the pentrator and maintain the crack-tip within the field of view.

The desired travel was 100 mm with the precision of positionning compatible with the system, as discussed below. The stage was designed by Strainoptic Technologies, Inc.

3.2.1. Selection Criterion for Stage Motion Drive Control

A motion control system typically consists of Translator/Driver, communications port, and power supplies. In most cases each of these components is sold separately by manufacturers. While they do provide flexibility to the user, they require the user to install cards in the computer. Experience has shown that motor controller cards installed in the computer sometimes tend to produce interference in image processing hardware. Purchasing individual components may also involve a considerable amount of user wiring.

These were some of the factors we considered during our market survey and decided to acquire a Superior Electric motor controller/driver. It offered the following advantages over other reputed manufacturers of motion control systems:

a) The Translator/Driver, communications port and power supply were all enclosed in one, stand-alone unit known as the "indexer" module. This arrangement minimizes user wiring requirements.

b) The communications port had a standard RS 232 serial interface.

c) The indexer is capable of handling a broad range of motion control applications from single repetative index motion up to 400 line programs.

d) The indexer's non-volatile memory can be programmed, edited, or manipulated through a serial or parallel port.

e) The indexer has an over-travel limit switch to prevent excessive travel in either direction. This factor was particularly important, since the optical probe could be damaged very easily by collision due to over travel.

f) This system is priced very competitively for the features it offers. Since it is a composite package, it saved us time that has to be normally invested in configuring a system.

3.2.2. Description of Selected System

The system consists of a Superior Electric 230 PI Indexer module and and MG1 motor. (FIGURE 6)

Indexer Module - The indexer module is a sheet-metal enclosure containing an indexer and a power supply for all motor and logic power requirements.

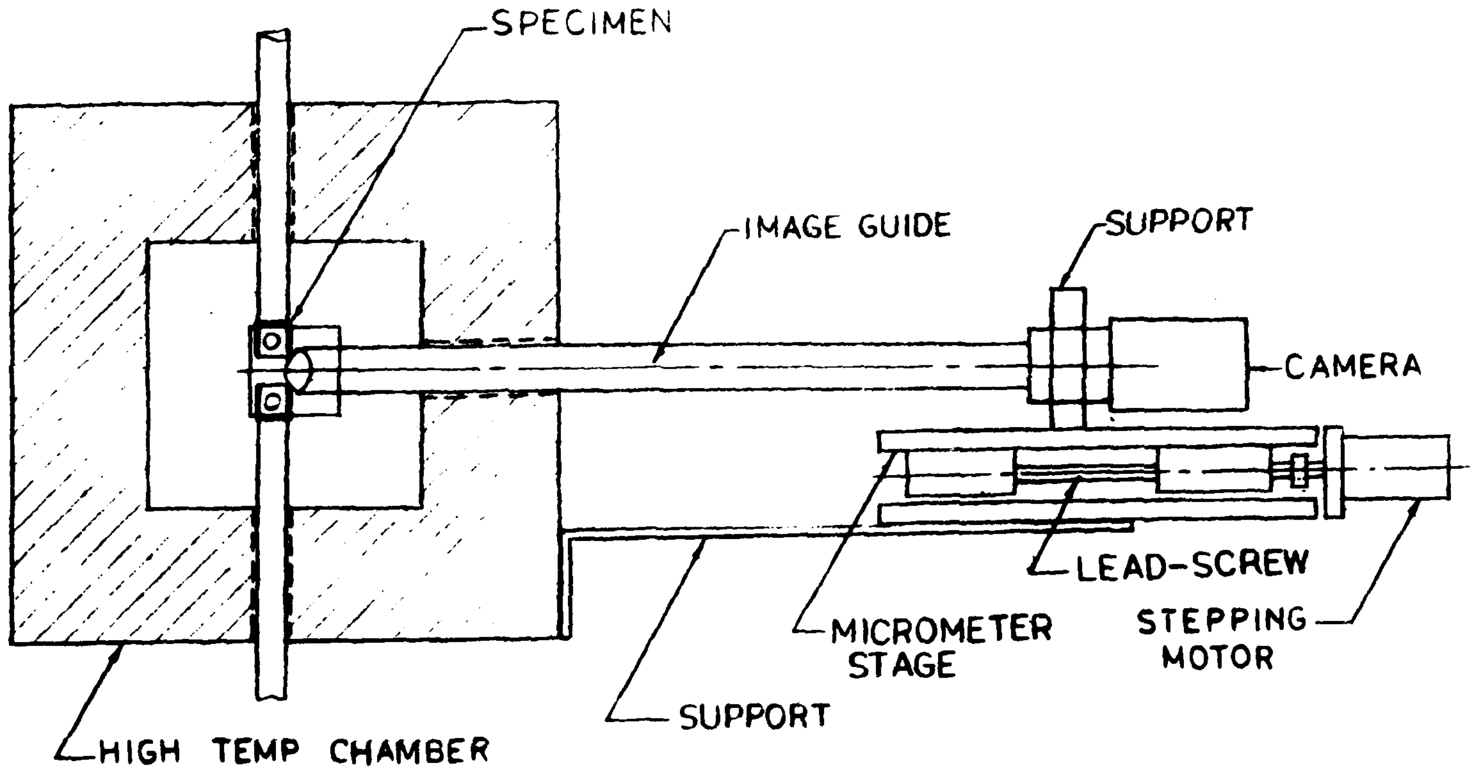

FIGURE : 5 CAMERA SET-UP FOR DIGITAL IMAGE ANALYSIS OF CRACK-TIP POSITION

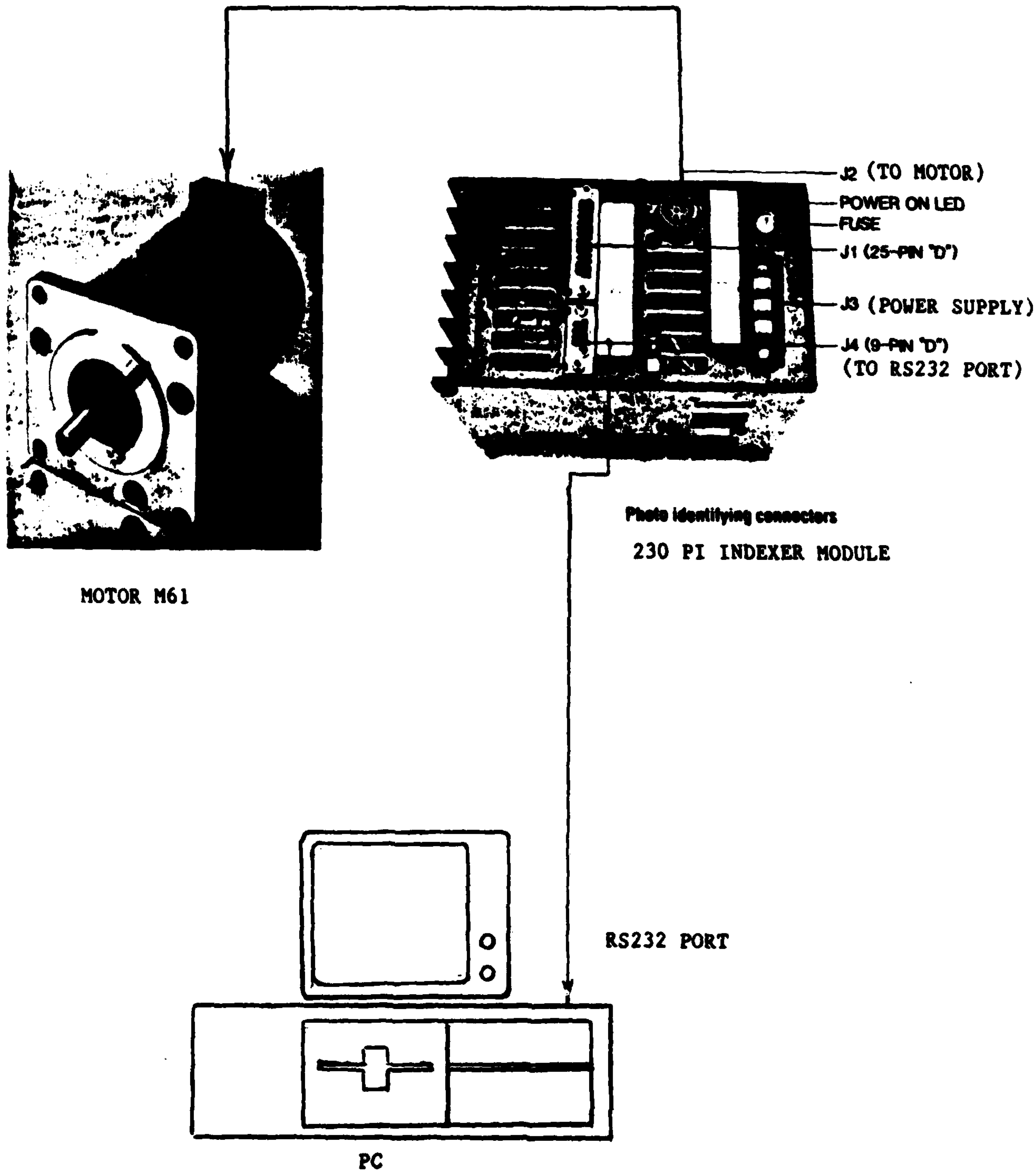
J2 (TO MOTOR)
POWER ON LED
FUSE
J1 (25-PIN 'D')
J3 (POWER SUPPLY)
J4 (9-PIN 'D')
(TO RS232 PORT)
Photo identifying connectors
230 PI INDEXER MODULE
MOTOR M61
RS232 PORT
PC

FIGURE 6

An indexer is a microprocessor-based programmable motion controller which contains the (a) translator, (b) oscillator/pulse generator, and appropriate logic and intelligence to control the speed, distance, limit switch inputs and other programmable functions.

Translator - a translator is an electronic device which accepts a command in the form of a pulse from the data source. It then translates or converts that pulse into the appropriate switching of the drive module power transistors to move the motor shaft one step, hence the name translator. The translator will accept the pulse or pulses provided by the data source and will change the motor speed to correspond with any change in frequency of pulses provided to the translator.

Oscillator/Pulse Generator - an oscillator is a digital pulse source which provides an alternate pulse source to allow manual control of the motor.

An indexer is a very cost effective means of control versus the expense of microcomputer programmable logic controller module. An indexer typcally takes in a command from a data source, an RS 232 computer interface, in our case, and then applies the appropriate number of pulses at the proper frequency to the translator portion of the system, thereby positionning the motor and load. An indexer is thus a device that is dedicated to the control of motion.

MG1 Motor - The MG1 is a brushless DC stepper motor. It is capable of converting digital signals from the indexer into fixed mechanical increments of motion. The motor provides angular increments of *1.8 degrees per step.*

Although motors with smaller angular increments were available, this was considered appropriate, since with a proper selection of lead screw pitch it was possible to achieve the required resolution. The load requirement is very small, hence the smallest available motor size (MG1) was selected.

Relevant Programmable Motion Control Features - The manufacturer has provided codes for each control option. These codes can be stored in the indexer's non-volatile memory. By assigning numbers to each of these codes, the user can program various control features. The indexer also has a 400 line non-volatile program memory. The user can call the codes in a program saved in the memory. Once set, the codes and the program reside in the memory permanently. During software development, Strainoptic Technologies, Inc., has factory set the following codes. (These codes are most relevant to system performance. For full detail, please refer to the Programmer's Manual for the 230 PI Indexer).

- L Codes - These codes are used to set parameters for each indexer. They are not part of an indexer program. These commands are made prior to any motion programming.

  Acceleration/Deceleration (L11):

  Sets the value, in pulses/sec./sec., for acceleration and deceleration. The same rate applies to both. Set at L11 500 pulses/sec./sec.

Clockwise and Counter Clockwise Software Travel Limit Switches (L18, L19):

When the absolute position of the motor exceeds the limits set by these switches in clockwise and counter clockwise directions a hold is placed on the motor.

Set at L18 4000 steps clockwise (from electrical home).
L19 4000 steps counter clockwise (from electrical home).

Translator Resolution (L70):

This sets the step resolution of the motor. It has been set to full step or 1.8 degrees. Set at L70 1.

Programming Codes (N, G, X, F) - Up to 400 lines of program instructions can be stored as a unique motion control program. Each program line is in a fixed format and is composed of a line number, a "G" code, an "X" field and "F" field. The significance of these codes is as follows:

N(nnn) Line Number: Sets the program line pointer to a specified line.

X (snnnnnn) Move direction and distance: Moves the motor in clockwise direction for the distance specified.

F(nnnnnn) Federate: Sets motor speed in pulses/sec.

G91 Incremental Mode: By issuing this command all motor moves are counted either plus or minus from present motor position.

<u>Indexer Program Function</u> - As mentioned earlier, the indexer communicates with the host computer. The host computer is capable of executing a program stored in the indexer memory by issuing "H" code commands through the RS 232 port. Following is a sample program, its function is to advance the motor by 800 steps at a predefined speed, acceleration/deceleration (set by L11 code), each time an "H" code command is issued by the host computer.

Typical Indexer program:

N001 G91 X+00000800 F0000500	Line 1 sets the indexer in incremental mode with G91 and the motor moves to position = current position + 800 pulses at a feed rate of 800 pulses.sec.

Typical Fortran subroutine to execute Indexer program:

Write (*, 10) 'H01'

<u>Function</u>

Unit 10 has been defined as the RS 232 serial port. H01 will be written into the RS 232 port in ASCII format. H01 is the CYCLE START command for the indexer. It will cause execution of the indexer program from line 1 to line 400. On completion of the execution the line pointer will be returned to 0. (Please note that L06 is set to 2 and L41 is set to 0 for this format).

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Closed loop and open loop operation - One key consideration behind selecting an open loop system is that the inertia of the system is very small. Hence, it is not likely to loose step in any of the operations. The error from one step to the next is noncumulative and is only 3% to 5%. This translates to ±0.09 degrees/step. This error is applicable to the motor alone and cannot be improved upon by having a closed loop system.

The feedback that will be part of the research program proposed in the Phase II will include consideration of the absolute specimen-position. A fixed reference will then be required to provide the verification of the absolute position, rather than the "conventional" feedback, related to the axis of the stage only.

3.3. Digital Image Analysis System

The Digital Image Analysis System assembled at Lehigh University and used in the Phase I research consists of a CCD high-resolution camera (installed on the translation stage described above), providing an RS-170 compatible output, to the data acquistion board.

The hardware of the image analysis system consists of DT2851 high resolution frame grabber for real time data acquisition. The image is captured during 33 msec. To utilize fast averaging and other image enhancing procedures, a DT 2858 Arithmetic Coprocessor is also installed into PC. It can provide high speed real-time image processing with the DT2851 frame grabber. The 512 x 512 x 16-bit frame processing includes N x M convolutions, frame averaging, division and arbitrary normalization. It has an on-board frame storage for one frame and 16-bit accuracy per pixel.

The process of data acquisition is usually repeated 2-5 times. Thus, an average picture is obtained, which is relatively free of random, hardware induced, noise. The image is digitized into 512 x 512 pixels and light intensity of each one is evaluated with 8-bit accuracy. The digitized image is used for analysis of the crack-tip position. The block diagram of the developed software package is shown in Figure 7.

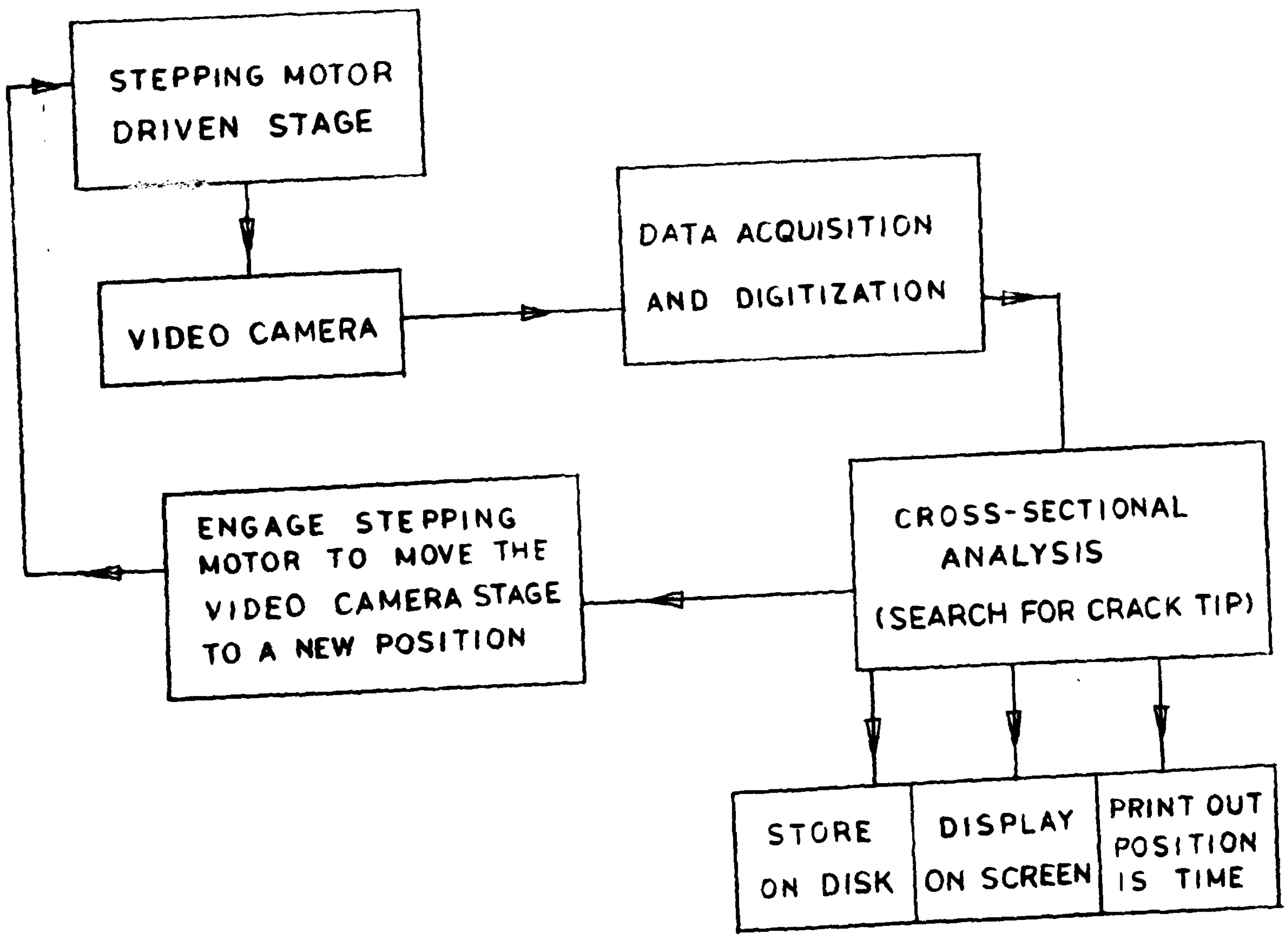

FIGURE: 7 DIGITAL IMAGE ANALYSIS BLOCK DIAGRAM

3.4. Software

3.4.1. Logic of the Automated Crack-Tip Follower (ACTIF) Software Package

Without loss of generality, let us assume that the crack is propagating from the top of the screen to the bottom. In every experimental set-up such postionning is possible by simple rotation of the camera head. Let us set the origin of the absolute coordinate system at the location of the tip of the crack before it started to grow.

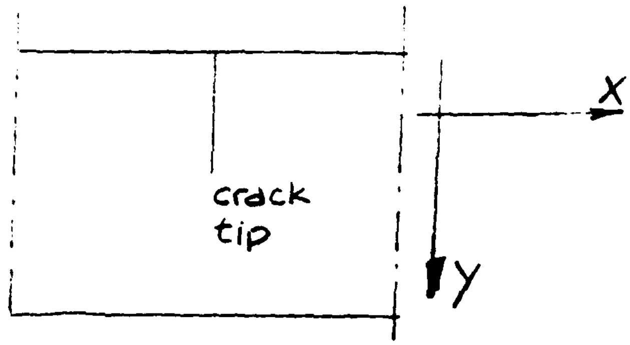

figure 8

The process of crack location, recording and decision on advance of the stepping motor is set as follows:

1) Adjust the camera head position, location, and lighting in such a way that the initial crack is visible on the screen similar to the sketch above.

2) Using the cursor, show the position of the reference scale on the screen. This information is needed for scaling of the visual image to its real size.

3) Enter information about the desired temporal length of the test and frequency of data acquisition.

4) Using the cursor, show the position of the crack-tip on the screen.

5) When everything is ready for a test hit (return), and process of the crack-tip following will be initiated.

6) The system will acquire the optical image and digitize it into 512 x 512 pixels, at each location the relevant light intensity will be acquired with 8-bit resolution, i.e. value between 0 and 255 will be assigned.

7) Since the crack is growing from the top and its initial position is known, the system will scan horizontally, starting 30 rows above the given crack-tip position (to ensure that we are above the actual crack-tip). The acquired light intensity along any particular row is analyzed, and the position of the crack line is determined, since at the crack line location value of light intensity is less than any place around this area.

After the scan of one row is completed, the system advances to the next row and the same process is repeated. At one instance of time, the crack line will not be detected, since we advanced below position of the actual crack-tip. This will signify the crack-tip position. The absolute coordinate and time will be stored, the system will wait for the prescribed time interval before the next picture is acquired, and the whole process will be repeated.

8) After several advances, the crack-tip will approach the lower end of the screen, i.e., it will arrive close to the boundary of the available optical image. At this point, the stepping motor will be engaged and the camera head will be linearly moved by a prescribed distance to ensure that the crack-tip is now at the upper part of the screen.

   Assuming parallel motion of the camera head, with respect to the specimen surface, the new position of the crack within the optical image can be easily calculated. On the other hand, by assuming slow rate of the crack-tip propagation and locating the position of the crack on the screen, the two positions can be compared to one another.

   In an unlikely event of a large crack advance, that occurred during the camera motion, the operator will be notified by a "beep" and this event will be noted on the data file, which contains all spatial and temporal information about crack-tip history. Thus, necessary adjustment can be implemented.

9) The system will now, again, return to step 7, and this process (steps 7 and 8) will repeat itself until the prescribed time limit is achieved or the specimen will fail catastrophically.

10) In the case, where information on the applied load is available in electronic form (analog or digital), it can also be fed into the system, thus providing all necessary information for automated analysis of the fatigue test results.

Since the objective of the Phase I was limited to the demonstration of feasibility, the software described above did not include additional alternative approaches that are highly desirable, to insure a full-proof industrial-environment operation. The complete software package will be more fully developed in the Phase II of this project.

4. RESOLUTION OF THE SYSTEM

The resolution of the crack-length measuring device is important, since it affects exponentially the precision determination of the fracture mechanic parameters that are tested.

A purely optical observation at room temperature has virtually no resolution limits, since the magnification of the observing microscope can be increased at will. A bonded sensor, such as crack-propagation gage introduces several potential inaccuracies:

a) The crack-tip of the sensor does not coincide with the crack-tip of the specimen.

b) The sensor consists of grid lines that are discretely spaced.

c) The instrument used for readout of a bonded sensor has limits of resolution.

The optical method proposed here has the resolution that depends of the objective lens used at the tip of the penetrator (See Figure 2 & 3).

a) Resolution of the Digital Image Analysis System

The full frame is resolved in 512 x 512 pixels. Selecting the magnification to observe a 6 mm (¼ in.) on the full-size screen, the resolution becomes:

6 mm/ 512 = 0.012 mm (.0005 in.).
Using a 3 mm image, one can increase the resolution to:

3 mm/512 = 0.006 mm (.00025 in.).

b) Resolution of the Stage: Positionning of the Penetrator

The step motor is geared 1:1 to the lead screw, ½" diameter - 20 TPI. The stepping motor controller resolves ½ step (400-½ steps/rev.) providing an overall position resolution:

.050 in./revolution/400 half-steps = 0.000125 in.

The stage was equipped with anti-backlash drive and 4 in. travel capabilities.

c) Resolution of the Optical System

Two concepts of optical systems transmitting the image between the two penetrators were tested (Figures 3 and 4). The resolution of the system using relay-lenses (Figure 4) is much greater than the resolution of the system user fiber-optic guide (Figure 3). The fiber-opptic image guide was constructed of 12 (12×10^{-6} m) fibers yielding a resolution that is nearly identical to the pixel resolution of the DIA system.

The overall resolution is, therefore, limited by the DIA system, and is 0.00025 in., approximately four times better than the precision required, initially for set-up as a target of this feasibility study.

5. TEST RESULTS AND CONCLUSIONS

5.1. System Components

Upon completion of the system design, the components were assembled and each individual performance verified.

Figure 9: Illustrates the Digital Image Analysis System used in this program.

Figure 10: Shows the stepping-motor driven stage, with the programmable indexer. The penetrator and camera are mounted on the stage.

Figure 11: Set-up used in the furnace for verification of the performance of optical materials at 2000° F.

Figure 12: Typical display of the crack-tip position on the monitor screen.

5.2. Test and Evaluation of the Optical System

5.2.1. Room Temperature Testing

The penetrator was assembled, for testing of both configurations, RELAY-LENS (Figure 3) and Fiber-Optic image guide (Figure 4).

Both configurations provided the desired image transmission. The relay-lens system yielded a slightly lower transmission effficiency, due to reflection losses on each lens surface.

The QUALITY of the image transmitted by the relay-lens model was considerably higher. The fiber-optic guide image, when carefully focused, (See Figure 13), (at higher magnification than used in operation), shows fiber-boundaries. The presence of these boundaries could adversely affect the crack detection ability of the Digital Image Analysis, when used at the same magnification level For this reason, we concluded that the relay-lens system should be preferred.

5.2.2. Elevated Temperature Testing

Presently available fiber-optic guides are limited in their high-temperature capabilities. Although several manufacturers advertise the availability of fused-silica fibers, not a single manufacturer was able to quote a coherent image conduit. Two manufacturers stated that they are presently working on this item and fused-silica image conduits will be available in the near future, (probably for the Phase II program). For the relay-lens penetrator, FUSED SILICA lenses were procured and installed as shown in Figure 3.

The assembled penetrator was installed in the high-temperature furnace in our laboratories, facing a specimen containing a naturally grown crack at 2000° F. The lens-system performed flawlessly.

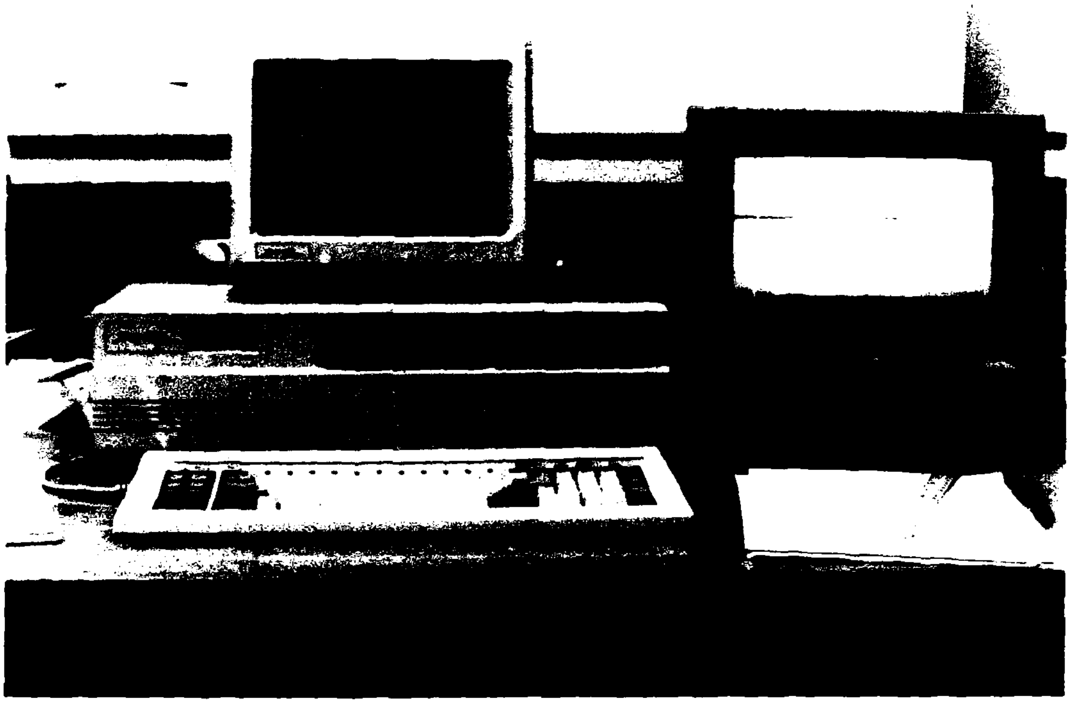

FIGURE 9: DIGITAL IMAGE ANALYSIS SYSTEM

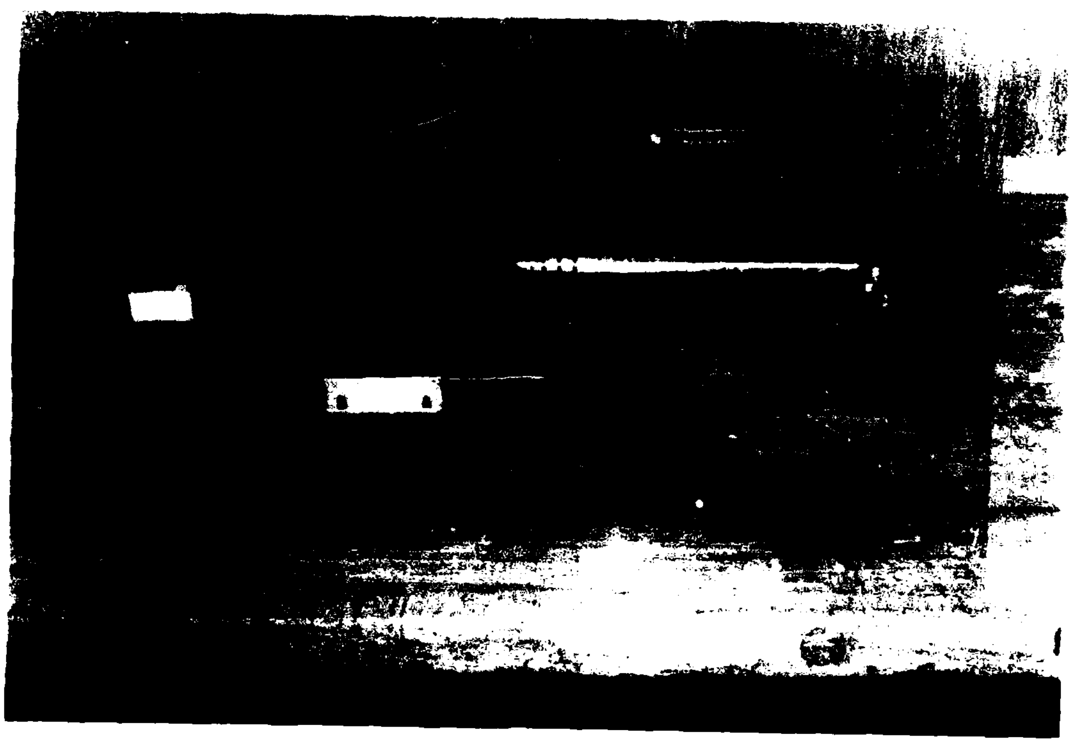

FIGURE 10: MOTION CONTROL STAGE

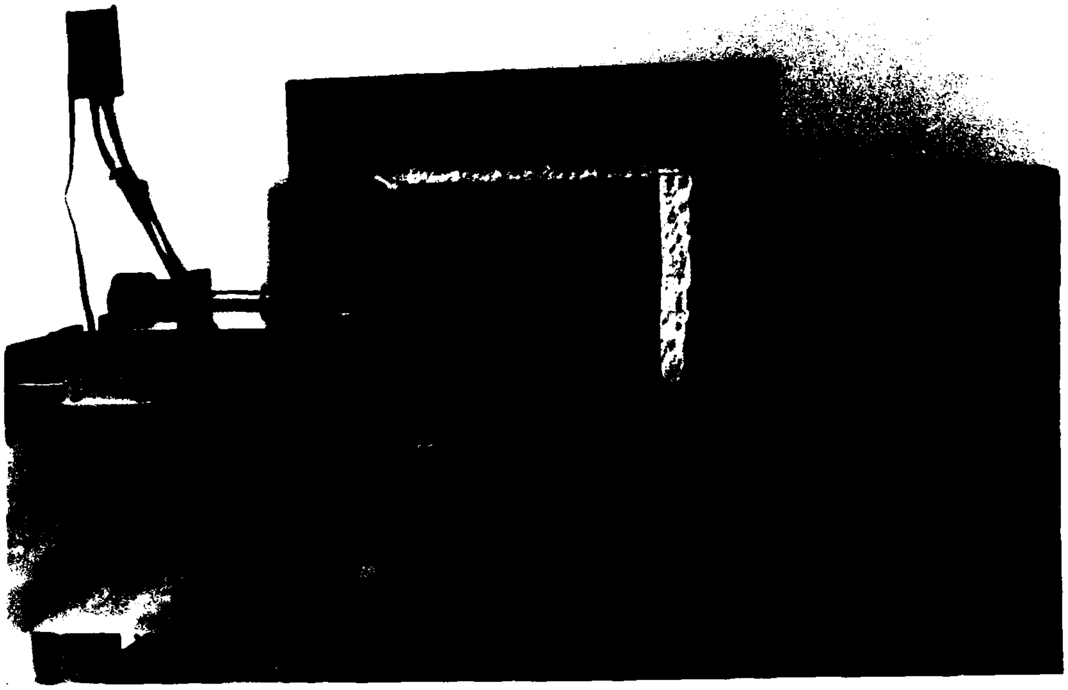

FIGURE 11: PENETRATOR USED TO OBSERVE A SPECIMEN INSIDE THE HIGH-TEMPERATURE FURNACE.

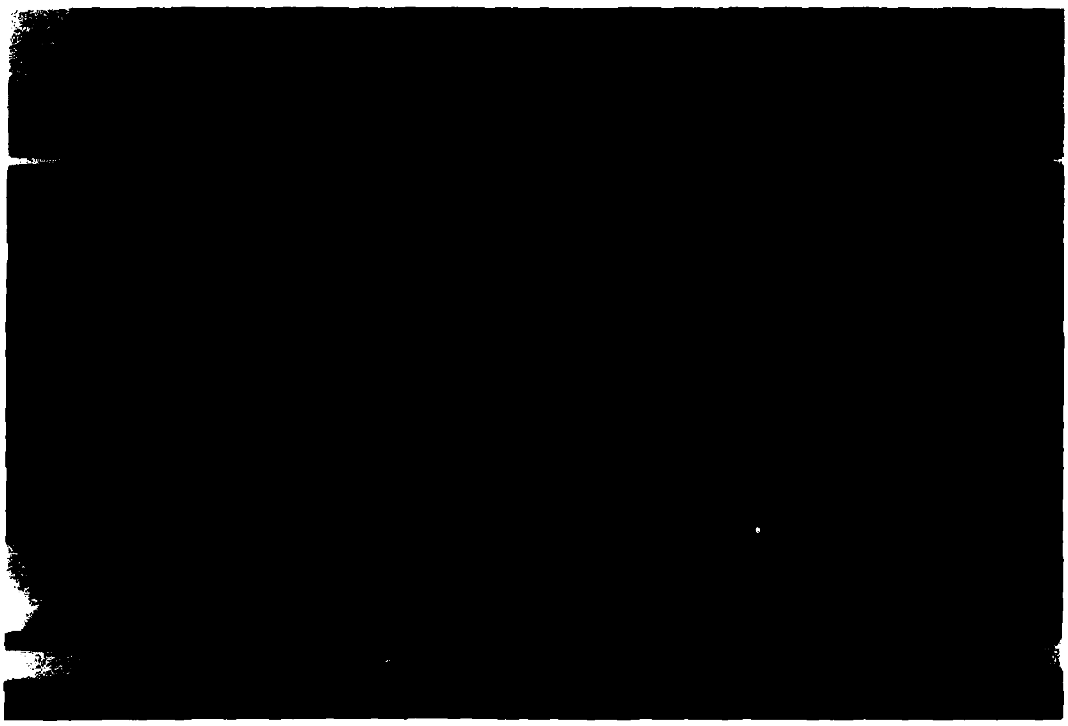

FIGURE 12: CRACK-TIP POSITION READOUT

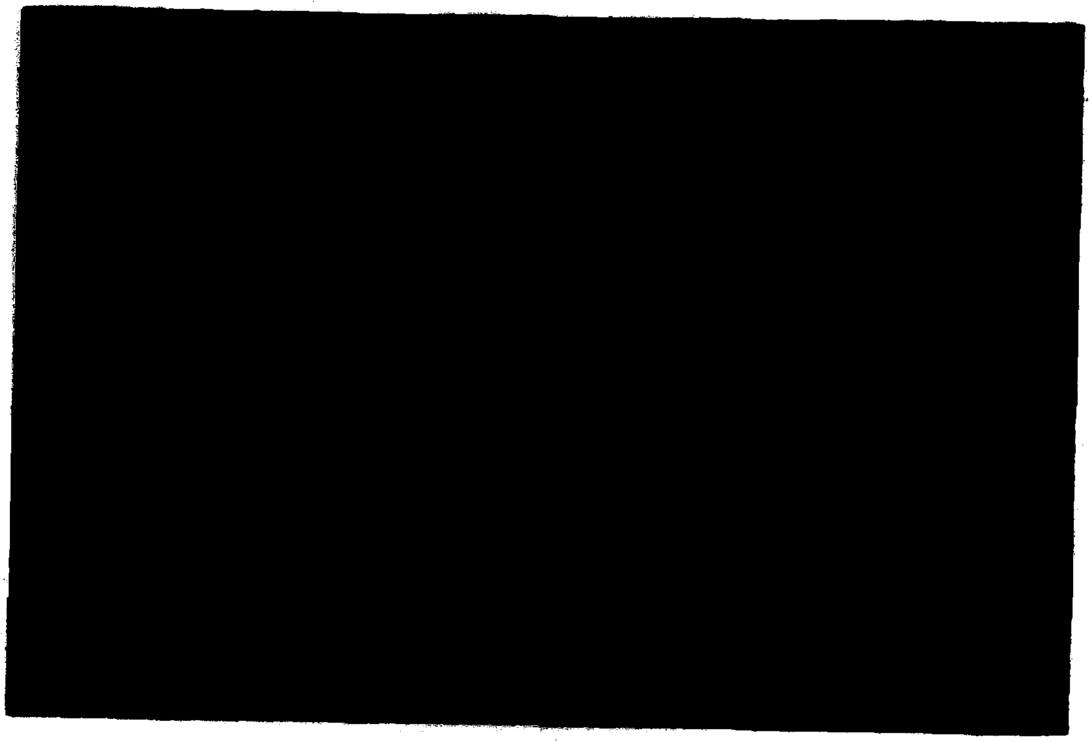

FIGURE 13: IMAGE TRANSMITTED BY FIBER-OPTIC GUIDE

After several 2000° F cycle, there was no visible trace of an optical surface degradation or lenses exposed to 2000° F, but some oxydation was present on all stainless steel surfaces. It is probably advisable to replace some st. st. components by ceramics, mostly for all future testing at high temperature.

The penetrator design was fully successful in separating the CCD camera from the high-temperature environment. A thermocouple measuring the temperature at the camera end yielded the following results:

Furnace Temperature	Penetrator Temp. at Camera Mount
RT	RT
1000° F	110° F
2000° F	145° F

A cut-off filter installed in front of the CCED sensor prevented the infrared radiation from reaching the camera.

From the above test, both at room temperature and at 2000° F, it can be concluded that the optical system can operate at 2000° F, and that the concept of a penetrator is feasible and practical.

5.3. Testing of the Positionning Stage

To evaluate the positionning motion, the stage was computer-driven to various positions, and requested to return to its "home" position. In all tests, the stage returned to the position within a fraction of a step, within a precision that exceeded our requirements. It was concluded that the motion control system is perfectly capable of performing the desired tasks.

5.4. Testing of the System

The system evaluation was performed on a system that included the Digital Image Analysis package (Figure 9) the positionning stage, with the penetrator and camera mounted on it (Figure 10) and the indexer driven by the software measuring the crack-tip position.

To assess the feasibility of the proposed method of detection of the crack-tip position using the Digital Image Analysis, and quantitatively determine the crack progress, the following procedure was used:

a) The surface showing a crack was positioned in front of the system.

b) After the initial focusing, the area was illuminated, for best contrast.

c) The screen cursor was used to set-up the scale factor and the boundaries.

d) Using the software developed and described above, the coordinates of the crack-tip were measured.

e) The surface containing the crack was moved to a new position, simulating the crack growth. This simulated motion was used in order to compare the change in (xy) tip-of-the crack coordinates measured by the Digital Image Analysis to the actual displacement measureed on a real scale.

f) The surface containing the crack was moved beyond the boundary set-up by the system to test the program ability of repositioning of the penetrator to a new position.

The results of these tests showed that the software designed was performed in accordance with out expectations, in particular:

- The crack-tip position coordinates were displayed correctly, as the crack-tip moved.
- Upon reaching the prescribed motion, the stage-driving motor was timely instructed to advance to its new position, within 0.001 in.

These results demonstrated the system operation, the software proficiency, and the feasibility of the concept.

5.5. Conclusions

From the test results obtained, it was possible to conclude that:

a) All the components needed to perform the targeted task were designed and tested at temperatures up to 2000° F.

b) An operational prototype, including all components, was assembled and tested.

c) The software designed for detection of a crack-tip using Digital Image Analysis performed this function, demonstrating the feasibility of the concept.

d) The research completed under Phase I has a broad significance. The proposed NEW METHOD is of interest to researchers in government and industry, and should be properly promoted pending Air Force release, ABSTRACTS will be mailed submitting the publication of the research results to:

   - Society for Experimental Mechanics.
   - ASTM - Committee of Fracture Mechanics (E24)
   - BSSM - British Society for Strain Measurements
   - SPIE - Society of Photo-optical Instrumentation Engineering

   In view of the novelty and originality of the optic, the acceptance of the publication is virtually secured.

6. RECOMMENDATION - FUTURE RESEARCH

The results of the Phase I Research reported above proved the feasibility of the concept, and demonstrated that fully automated system, based on the Digital Image Analysis can be designed and operated, providing a continuous monitoring of the crack-tip position, at room or elevated temperature.

6.1. Extension of Temperature Range to 2700° F

Such a system can contain fused-silica optics, to operate at 2000° F, or employ other readily available optical materials, such as sapphire to extend the operational temperature to approximately 3000° F.

In addition to investigation of the increased temperature capabilities, the future research (to be included in the Phase II objectives) should include:

6.2. Research on Methods of Absolute Position Indexing Using Digital Image Analysis

These methods should include usage of the specimen edge and/or reference position marks in the specimen, for verification of the absolute image position, with a feedback provision for updating of the stage "zero".

6.3. Illumination Methods

The illumination methods needed to provide a high-contrast image needed for the accurate measuring is affected by the specimen temperature. Above 2000° F, the specimen radiation in the visible range becomes very high and spectral filtering approach will be needed to enhance the crack visibility.

6.4. Handling Methods in a Variable Temperature Loading Spectrum

The Phase I tests were conducted at room temperature and at 2000° F (constant temperature) steady state. In a variable temperature situation (ramp) specimen displacement and optics changes must be analyzed and incorporated in the Digital Image Analysis, for proper data interpretation. The research and experimental program should be included in the Phase II research, suggesting procedures to deal with thermal gradients, assessing the precision and developing proper thermal compensation methods.

6.5. Software Development

The software development appears to be the most desirable part of the future research. In addition to the USER FRIENDLY features, that include on-the-screen instructions and help, the additional developments needed are:

- Inclusion of the machine input, providing N (number of cyles), as a control parameter.
- Graphic capabilities and output.
- Calculation of parameters.

Strainoptic intends to submit a Phase II proposal, including all of the above topics, and additional objectives that appear desirable design objectives.

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